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19. ABSTRACT (Continue on reverse if necessary and identify by block number) Significant progress has been made in understanding carrier collection and stimulated emission in ultra-thin semiconductor quantum wells. Continuous wave low threshold laser operation has been demonstrated with quantum wells as thin as one monolayer (3.5Å). A more complete theory of the scattering and collection of carriers near a quantum well has been proposed and shown to be quantitatively consistent with previous experiments and the unexpected experimental results (monolayer lasers) demonstrated in this program. We have shown that the spatial extent of the wave function rather than the well width is the more fundamental length parameter when considering the collection of carriers by a quantum well. The first time resolved data on phonon assisted stimulated emission was demonstrated. The data is continued				
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18. phonon assisted stimulated emission, alloy disordering, photoluminescence, carrier recombination, staggered transition

19. consistent with Holonyak's prediction of stimulated phonon emission. This could open up an entirely new class of electron-phonon-photon interactions in condensed matter.

Other important results include: the first demonstration of laser action on a staggered (real space) transition; first tunneling through a 'bound state' in a strained layer resonant tunneling device; and the demonstration that ultra-thin quantum wells can be preserved at elevated temperatures with a Ga overpressure.

**CARRIER COLLECTION AND SCATTERING IN
QUANTUM WELL AND SUPERLATTICE DEVICES**

DAAL-03-87-K-0051

Final Report

Statement of the Problem

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The objective of this experimental program is to understand and quantify the parameters that influence the transport (perpendicular) and carrier collection mechanisms of electrons and holes at the heterobarrier interfaces in semiconductor quantum wells and superlattices. This work is relevant to the design of optoelectronic and electronic components (laser diodes, heterojunction bipolar transistors, modulation doped field effect transistors, solid state photomultipliers) which are of great interest to the commercial and defense communities. The output of this program has been: (1) a set of design rules based on the physics that governs carrier collection in ultra thin layered heterostructures and (2) the proposal/demonstration of new device structures that utilize energy dependent carrier collection and/or the high collection efficiency of ultra-thin quantum wells.

Summary of the Most Important Results

The most important accomplishments and their relevance to the SDIO/IST goals are:

1A) First demonstrations of laser operation of monolayer thick quantum wells.

- laser operation of **one monolayer** (3.25 Å) InAs-GaAs strained layer pseudomorphic quantum well
- **continuous wave low threshold laser** operation of a 2 monolayer InAs-GaAs quantum well at 77K
- laser operation of a 2 monolayer GaAs-AlGaAs quantum well
- continuous wave low threshold laser operation of a 3 monolayer GaAs-AlGaAs quantum well

1B) Explained basic physics of why monolayer thick lasers are possible even though these results were unexpected based on previous knowledge.

The near term impact of accomplishments 1A and 1B:

- * Knowledge of pseudomorphic InGaAs-GaAs has resulted in funding from Martin Marietta to develop solid state lasers for underseas communications (satisfies objective of novel lasers for DoD applications)

- * Makes possible the use of GaAs based electronics with longer wavelength lasers which can be designed so that the substrate can be either transparent or absorbing (consistent with long term goal of **monolithic optoelectronic circuits**)

The long term impact of accomplishments 1A and 1B:

- * We have already demonstrated that an InAs-GaAs laser operates more than an electron volt in energy above the InAs band edge. If we repeat this experiment with wider band gap materials (which is now feasible based on recent advances in crystal growth) it **may be possible to achieve laser operation 1-1.5 eV above the band gap of a pseudomorphic quantum well made from a material with a bulk band gap greater than 1.5eV** (which has not been possible with bulk materials or even traditional quantum wells). This would have a tremendous impact on the field optical data storage and data processing. (Consistent with long term goal of developing novel lasers and optical components.)
- 2) First confirming observation of **phonon assisted stimulated emission** . Also, demonstrated the thinnest quantum well to exhibit phonon assisted stimulated emission. Phonons play an important role in thermalizing injected carriers in laser diodes and are often the limiting factor in high speed electronic devices. (The relevance is that the impact of phonons in quantum wells must be understood in order to design devices and understand their limitations.)
 - 3) **First time resolved data of phonon assisted stimulated emission** . Holonyak and co-workers have suggested that phonon assisted stimulated emission may actually involve **stimulated phonon emission**. If so, this would open up an entirely new class of electron-photon-phonon interaction in condensed matter. All of our data to date is consistent with Holonyak's prediction but we have not been able to conclusively verify the prediction. (The relevance is that new device concepts could be developed if the predicted interaction is conclusively verified.)
 - 4) **First tunneling through a bound state in a strained layer InGaAs-GaAs-AlAs resonant tunneling structure**. Demonstrated the tunability and importance of scattering in the transport of hot majority carriers through a double barrier resonant tunneling structure. (Relevant to the development of high speed/density circuits that need monoenergetic electrons/holes.)
 - 5) Developed a **simple method for incorporating quantum well properties into drift-diffusion semiconductor models**. The utility of this model is that it allows us to incorporate complex quantum mechanical computations done by others into a relatively simple framework. (Relevance is that it allows us to predict general trends and gives us time to get things done like items 1-4,6.)

- 6) Demonstrated that Ga over pressure enhances the stability of GaAs-AlGaAs quantum wells during high temperature thermal processing. Demonstrated that InAs-GaAs pseudomorphic quantum wells are quite stable at elevated temperatures. Relevance is that we know now that ultra-thin quantum wells can be fabricated and processed into devices while maintaining their structural stability. (Relevance to SDIO/IST is that ultra-thin quantum wells can be grown and will survive processing into devices.)
- 7) First demonstration of laser action on a staggered (real space) transition. Relevance is that it may be possible to bypass some of the difficulties that indirect band gap materials pose for optical devices (leading to novel optical devices).

DAAL 03-87-K-0051 PUBLICATIONS

"Stimulated visible light emission from ultra-thin GaAs Single and multiple quantum wells sandwiched between indirect gap ($\text{Al}_{0.49}\text{Ga}_{0.51}\text{As}$ confining layers," J.H. Lee, K.Y. Hsieh, Y.L. Hwang and R.M. Kolbas, Appl. Phys. Lett. 56, No. 20, pp. 1998-2000 (14 May 1990).

"Photoluminescence and stimulated emission from monolayer thick pseudomorphic InAs single quantum well heterostructures," J.H. Lee, K.Y. Hsieh and R.M. Kolbas, Phys. Rev. B. 41, pp. 7678-7684 (15 April 1990).

Stimulated emission from monolayer thick $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -GaAs single quantum well heterostructures," J.H. Lee, K.Y. Hsieh, Y.L. Hwang and R.M. Kolbas, Appl. Phys. Lett. 56, No. 7, pp. 626-628 (12 Feb 1990).

"Stimulated emission in ultra-thin (20Å) $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -GaAs single quantum well heterostructures," Y.C. Lo, K.Y. Hsieh, and R.M. Kolbas, Appl. Phys. Lett. 52, pp. 1853-1855 (30 May 1988).

"Phonon assisted stimulated emission in thin (<55Å) AlGaAs-GaAs-GaAs single quantum wells," Y.C. Lo and R.M. Kolbas, Appl. Phys. Lett. 53, pp. 2266-2268 (5 Dec 1988).

"Carrier recombination dynamics in thin InGaAs-GaAs single quantum well heterostructures," S.D. Benjamin, N.G. Anderson, and R.M. Kolbas, Quantum Electronics and Laser Science Conference 1989 Technical Digest Series Vol. 12, 84 (1989).

"Laser properties and carrier collection in ultra-thin quantum well heterostructures," R.M. Kolbas, Y.C. Lo, and J.H. Lee, IEEE Journal Quantum Electronics 26 pp. 25-31 (Jan 1990).

"Time resolved phonon assisted stimulated emission in quantum well heterostructures," 1989 Device Research Conference, IEEE Trans. Electron Devices **36**, No. 11, p. 2613 (Nov. 1989).

"Time resolved phonon assisted stimulated emission," S.D. Benjamin, J.H. Lee, Y.L. Hwang, T. Zhang and R.M. Kolbas, to be submitted to Appl. Phys. Lett.

"Stimulated emission and anomalous absorption in ultra-thin quantum well heterostructures," D. Zhang, Y.L. Hwang, T. Zhang, J.H. Lee and R.M. Kolbas, to be submitted to Appl. Phys. Lett.

"Stimulated emission from monolayer thick quantum well heterostructures," J.H. Lee, K.Y. Hsieh, and R.M. Kolbas, 1989 Device Research Conference, IEEE Transactions of Electron Devices **36**, No. 11, p. 2613 (Nov. 1989).

"Enhanced/suppressed interdiffusion of In_{0.3}Ga_{0.7}As-GaAs-AlGaAs strained layers by controlling impurities and gallium vacancies," K.Y. Hsieh, Y.L. Hwang, J.H. Lee, and R.M. Kolbas, presented at the 1989 Electronic Materials Conference. To be published Journal of Electronic Materials.

"Effects of a low temperature GaAs buffer layer on the interdiffusion of GaAs/AlGaAs heterostructures during thermal annealing," presented at the 6th Conference on Semi-insulating III-V Materials, Toronto, May 13-16, 1990; also to be published in the proceedings of the 6th Conference on Semi-insulating III-V Materials.

"The elimination of channel depletion caused by surface low temperature GaAs in a GaAs MISFET structure," Y.L. Hwang, W.L. Yin, J.H. Lee, T. Zhang, R.M. Kolbas and U.K. Mishra, to be presented at the 1990 Electronic Materials Conference; also, paper in preparation for the Journal of Electronic Materials.

Publications that got out the door while waiting for a contract number:

"High efficiency carrier collection and stimulated emission in thin (50Å) pseudomorphic InGaAs quantum wells," N.G. Anderson, Y.C. Lo and R.M. Kolbas, Appl. Phys. Lett. **49**, 758 (1986).

"Stimulated emission from ultra-thin (6.6Å) InAs/GaAs quantum well heterostructures grown by atomic layer epitaxy," Appl. Phys. Lett. **50**, 1266 (1987).

"Negative differential resistance in a strained layer quantum well structure with a bound state," G.S. Lee,

K.Y. Hsieh, and R.M. Kolbas, J. Appl. Phys. 62 , 3453 (1987).

Personnel Supported/Degrees Granted

Jung-Hee Lee (Ph.D. expected July 1990, Electrical and Computer Engineering)

S. David Benjamin (M.S. granted June 1988, Ph.D. expected in 1991)

Kuang-Yeu Hsieh (Ph.D. granted December 1989, Material Science) currently working as a post doc in the Material Sciences Department NCSU, MBE of thin film high T_c superconductors

Barbara Frank (M.S. granted June 1989) currently working at IBM on semiconductor lasers

Yaw Cheng Lo (Ph.D. January 1989, Electrical and Computer Engineering) currently employed at Kodak working in semiconductor process development

Dahua Zhang (M.S. granted June 1990) continuing on project toward Ph.D.

Other students supported (less than 1/4 time) to provide specialized skills required for the program: Y.K. Sin (processing), Y.L. Hwang and T. Zhang (MBE crystal growth)

Robert M. Kolbas, Principal Investigator